

Life-Cycle Analysis of Greenhouse Gas Emissions and Water Consumption – Effects of Coal and Biomass Conversion to Liquid Fuels as Analyzed with the GREET Model

Energy Systems Division

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1. INTRODUCTION

The U.S. transportation sector is the second-largest consumer of energy, accounting for more than 70% of U.S. petroleum consumption, and its demand was 14.4 million barrels per day oil equivalent in 2015 (US EIA 2016). The huge demand for transportation fuels and the limitations of crude oil supplies make it imperative to develop alternative transportation fuels from unconventional feedstocks, including oil sands, shale oil, biomass, and coal (National Academy of Sciences 2009). Successful development of such alternative fuels depends on cost competitiveness, environmental sustainability, and social sustainability.

As of January 1, 2016, EIA estimated that the demonstrated reserve base of coal in the U.S. is 477 billion short tons, and coal resources are larger than the remaining natural gas (NG) and oil resources on an energy basis (US EIA 2017). The vast reserves of coal in the U.S. provide a significant incentive for the development of processes for coal conversion to liquid fuels (CTL). However, current CTL technologies are less energy-efficient than petroleum refining, have greater greenhouse gas (GHG) emissions than petroleum fuels, and are not economically competitive with relatively inexpensive petroleum (Department of Defence 2014).

One of the major technology opportunities to improve the environmental sustainability of CTL is to supplement coal with biomass feedstocks. Combined agricultural resources, energy crops, forestry resources, and wastes are estimated at 343 million dry tons in 2017, and are projected to reach 1.2 billion dry tons under a base-case scenario and 1.5 billion dry tons under a high-yield scenario by 2040 (U.S. Department of Energy 2016). Many studies have shown that the use of biomass feedstocks could reduce GHG emissions via coal-and-biomass-to-liquid (CBTL) pathways. Xie, Wang, and Han (2011) evaluated two approaches to reducing CTL GHG emissions, namely, including carbon capture and storage (CCS) technology and using biomass as a co-feedstock. Compared to petroleum diesel, diesel from 100% coal increases well-to-wheels GHG emissions by over 200% without CCS and 5–29% with CCS. Without CCS, when forest residue accounts for 61% of the total dry mass input, Fischer-Tropsch (FT) diesel produces GHG emissions equivalent to those of petroleum diesel. If forest residue accounts for 100%, GHG emissions of FT diesel are 77% lower compared to petroleum diesels. Han et al. (2013) conducted well-to-wake (WTWa) analysis of bio-based aviation fuels from three pathways: hydroprocessed renewable jet (HRJ) fuel, FT jet fuel, and pyrolysis jet fuel. Compared to petroleum jet fuel, WTWa GHG emissions of FT jet fuel (a mixture of 20% corn stover and 80% coal by weight) increased by 71% without CCS and decreased by 30% with CCS. With 100% corn stover, WTWa GHG emissions of FT jet fuel decreased by 71% without CCS. For pyrolysis jet fuels with biochar combustion for power generation or biochar for soil amendment for carbon sequestration, WTWa GHG reduction was 68% or 76%, respectively.

Recently, Altex Technologies Corporation (Altex, hereinafter) and Pennsylvania State University have developed a hybrid technology to produce jet fuel from a mixed feedstock of coal and biomass. The overall objective of Altex's project is to raise the technology readiness level from 4 (prototype-scale testing in a laboratory environment) to 5 (pilot-

scale testing in a relevant environment), and develop and test a pilot-scale system producing > 1 barrel/day. Collaborating with Altex, Argonne National Laboratory expanded and used the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model (Argonne National Laboratory 2015) to assess life-cycle GHG emissions and water consumption of this hybrid technology. The GREET model includes various feedstocks, conversion technologies, and fuels. In addition, the GREET model includes all transportation modes, including road, rail, marine, and air transportation. For this project, we expanded the GREET model to include wheat straw farming and collection, biomass densification and transportation, the CBTL process (feedstock inputs, energy use, fuel and char production, and gas emissions), char to landfill (Char-LF), and char for combined heat and power (Char-CHP). However, a caveat is that the model for this study was built on GREET 2015, and some minor revisions were included in the GREET 2016 model (Argonne National Laboratory 2016).

Specific issues that Argonne was asked to address included (1) GHG emissions of biomass feedstocks (e.g., corn stover, switchgrass and wheat straw), in g CO₂e/dry ton feedstock, from the farming field to the refinery gate; (2) WTWa GHG emissions and water consumption of CBTL fuel composed of 85 wt% coal and 15 wt% biomass; and (3) the break-even point of biomass in the feedstocks and paths forward to achieve 84 gCO₂e per megajoule (MJ) (the WTWa GHG emissions level of conventional jet fuel).

2. METHODOLOGY

2.1 LIFE-CYCLE ANALYSIS SYSTEM BOUNDARY AND FUNCTIONAL UNIT

The system boundary of this life-cycle analysis (LCA) study encompasses all operations related to coal mining and cleaning, coal transportation, biomass farming and harvesting, biomass densification and transportation, fuel production, fuel transportation and distribution, and jet fuel combustion (Figure 1). These WTWa stages can be divided into Well-to-Pump (WTP) stages and Pump-to-Wake (PTWa) stages. The PTWa stages include the jet fuel combustion, while the WTP stages include the rest of the WTWa stages. In addition, the system boundary includes the indirect GHG emissions and energy and water consumption associated with materials and energy production, such as fertilizer production and application. However, the indirect GHG emissions and energy and water consumption associated with the infrastructure materials and equipment used in coal mining and cleaning, biomass farming, and fuel production are generally much smaller than those associated with fuel production and combustion, and therefore are not included (Wang et al. 2011). The functional unit of this LCA is 1 MJ of jet fuel on the basis of the lower heating value (LHV).

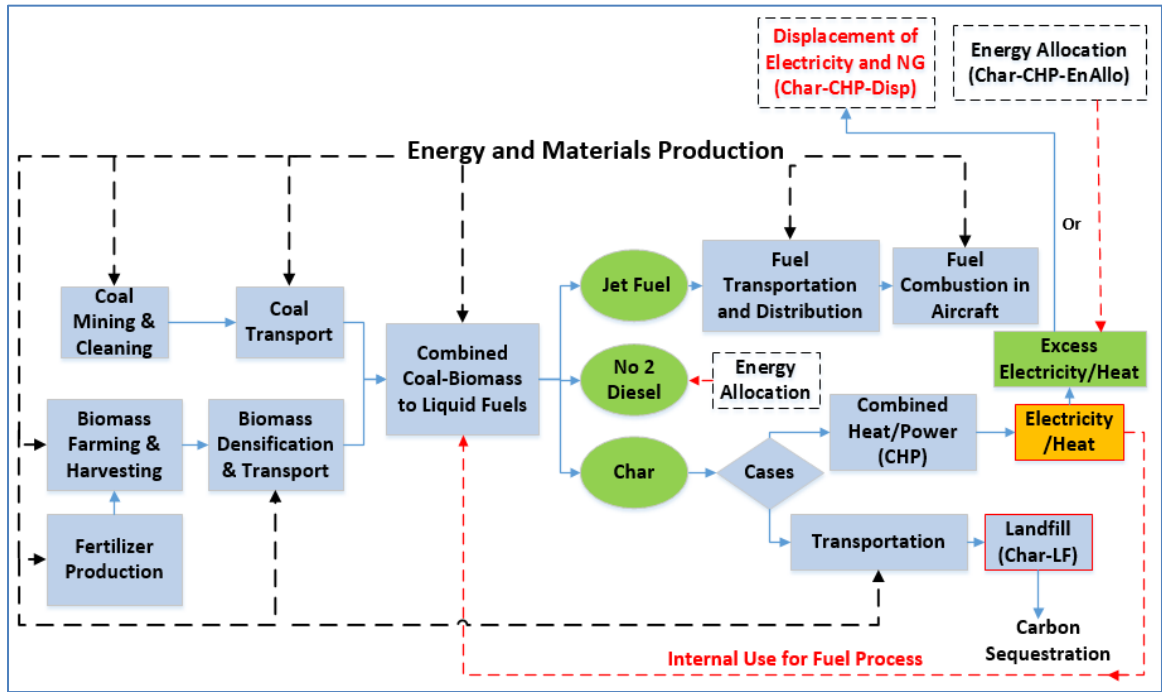


Figure 1. Life-cycle analysis system boundary of combined coal and biomass conversion to liquid fuels (CBTL): coal mining and cleaning, biomass farming and harvesting, fertilizer production, coal transportation, biomass densification and transportation, fuel processing, fuel transportation and distribution, and fuel combustion in aircraft

2.2 COAL AND BIOMASS FEEDSTOCKS

The coal resource utilized in Altex’s CBTL technology is lignite coal. Lignite coal (brown coal) is considered the lowest quality rank of coal because of its relatively low heating content. However, lignite coal has a high content of volatile matter, which makes it easier to convert into gas and liquid fuels than other higher-ranking coals. The coal energy content and carbon ratio are listed in Table 1. In this study, coal is assumed to be from surface mining. The energy consumption data for lignite coal mining and cleaning are also summarized in Table 1 (Altex Technologies Corporation 2016). The process energy sources include diesel, gasoline, and electricity, and the total energy consumption rate is 15,286 Btu/MMBtu of coal mined and cleaned. For surface coal mining and processing, the water consumption factor is 2.6 gal/MMBtu coal (Argonne National Laboratory 2016, Lampert, Cai, and Elgowainy 2016). During coal mining and cleaning, methane (CH_4) formed during coalification can escape into the atmosphere. Burnham et al. (2012) reported CH_4 emissions during coal mining and post-mining operations. The average CH_4 emissions

were estimated to be 49.5 g CH₄ per MMBtu (or 535 g/ton) of surface-mined coal. Other non-combustion emissions during coal mining and cleaning include volatile organic compounds (VOCs), PM₁₀ and PM_{2.5}, which are also listed in Table 1.

Table 1. Lignite coal energy content, carbon ratio, energy consumption for surface coal mining and cleaning, and non-combustion emissions during coal mining and cleaning

Lignite coal energy content and carbon ratio	Value	Data source
LHV (MMBtu/ton)	10.6	Altex
C (wt%)	63%	Altex
Energy use in surface lignite coal mining and cleaning^a	15,286	Altex
Diesel fuel (Btu/MMBtu)	11,671	Altex
Bio-diesel fuel (Btu/MMBtu)	897	Altex
Gasoline (Btu/MMBtu)	223	Altex
Electricity (Btu/MMBtu)	2,495	Altex
Non-combustion emissions during coal mining and cleaning		
VOCs (g/MMBtu)	6.8	GREET
PM ₁₀ (g/MMBtu)	12	GREET
PM _{2.5} (g/MMBtu)	1.5	GREET
CH ₄ (g/MMBtu)	49.5	GREET

^aThe calculated energy consumption values were based on the LHV of lignite coal.

Biomass feedstocks considered in this study include corn stover, switchgrass, and wheat straw. Table 2 summarizes the energy and material flows associated with cultivating and harvesting these biomass feedstocks, which are based on the latest updated values (Canter, Qin, et al. 2016, Argonne National Laboratory 2015, U.S. Department of Energy 2016). For corn stover, corn grain and stover are harvested separately with two passes (first pass for grain and second pass for corn stover). The second-pass energy consumption is assigned to corn stover. For wheat straw, the collection was modeled in the U.S. Department of Energy (2016). The supplemental fertilizers (N, P₂O₅ and K₂O) for corn stover and wheat straw are applied to replace the nutrients in the harvested biomass (Canter, Dunn, et al. 2016, Argonne National Laboratory 2015), because if corn stover and wheat straw remain on the field, these nutrients in biomass could enter the soil and be available for future crops. In this study, we also considered N₂O emissions from below- and above biomass decay and fertilizer application; N₂O emission factors for N in biomass and synthetic fertilizer are assumed to be 1.225% and 1.525% (N in N₂O as % of N in N biomass and fertilizer), respectively, as shown in Table 2 (Argonne National Laboratory 2015, Intergovernmental Panel on Climate Change 2006). In this analysis, water use is defined as the amount of water withdrawn from freshwater sources. Han, Tao, and Wang

(2017) assumed that corn stover does not consume water, since irrigation is mainly for corn farming and not for corn stover harvesting. We used the same method for corn stover and wheat straw in this study. There is no irrigation water demand for switchgrass farming (Argonne National Laboratory 2015, Lampert et al. 2015).

Table 2. Biomass farming energy and fertilizer use, and biomass N content and N₂O emission

	Corn stover ^a	Switchgrass ^a	Wheat straw ^b
Farming energy and fertilizer use			
Farming energy use (Btu/dry ton)	192,500	177,700	199,600
N fertilizer (g/dry ton)	7,000	7,300	4,987
P ₂ O ₅ (g/dry ton)	2,000	100	1,269
K ₂ O (g/dry ton)	12,000	200	6,895
Herbicide (g/dry ton)	0	28	0
Biomass N content and N₂O emission			
N content in biomass (%)	0.77%	0.50%	0.55%
N ₂ O emission conversion rate from N in biomass (N in N ₂ O as % of N in biomass)	1.225%	1.225%	1.225%
N ₂ O emission conversion rate from N in fertilizer (N in N ₂ O as % of N in N fertilizer)	1.525%	1.525%	1.525%

Data sources: ^aArgonne National Laboratory (2015) and ^bCanter, Qin, et al. (2016)

Unprocessed biomass often has low volumetric energy and bulk density and is aerobically unstable, making handling and transportation inefficient. Densification is one way to increase the volumetric energy density and overcome handling and transportation difficulties. The farming energy use summarized in Table 2 includes the energy demand for baling. For densification cases, this study assumed that the bales are further densified into pellets (small compressed pieces of biomass produced using hammer and pellet mills). The consumption rates of electricity and natural gas (NG) for bale-to-pellet densification were 81,891 and 75,120 Btu/dry ton, respectively, as shown in Table 3 (Altex Technologies Corporation 2016). We assumed that the biomass was transported by a heavy heavy-duty 53-ft flatbed trailer (25-ton and 106-m³ capacity) with fuel economy of 7.4 miles per diesel gallon equivalent (MPDGE), and the one-way travel distance was assumed to be 53 miles. Because pellets are easier to store, handle, and transport than bales, we assumed that the dry matter losses are 2.0% for bales and 0.0% for pellets.

Table 3. Energy consumption for biomass densification, biomass characterization, and transportation of various crops^a

	Corn stover bales	Corn stover pellets	Switchgrass bales	Switchgrass pellets	Wheat straw bales	Wheat straw pellets
Energy consumption for biomass densification (bales to pellets)						
Electricity (Btu/dry ton)	NA	81,891	NA	81,891	NA	81,891
NG (Btu/dry ton)	NA	75,120	NA	75,120	NA	75,120
Biomass characterization						
Bulk density (kg/m ³)	137	587	169	641	137	587
LHV (MJ/dry ton)	15,526	15,526	15,242	15,242	11,184	11,184
Energy density (MJ/m ³)	2,352	10,049	2,847	10,770	2,249	9,612
Moisture (%)	12%	6%	12%	6%	12%	6%
Transportation^b						
Truck payload (dry ton/load)	14	24	17	24	14	24
Energy consumption (Btu/dry ton)	131,288	78,929	106,449	78,929	131,288	78,929

^aData source: Altex Technologies Corporation (2016).

^bHeavy heavy-duty 53-ft flatbed trailer (25-ton and 106-m³ capacity) with fuel economy of 17,498 Btu/mile, and one-way travel distance of 53 miles.

2.3 COAL AND BIOMASS TO LIQUID FUELS CONVERSION PROCESS

As the proposed hybrid technology contains trade proprietary information, detailed descriptions of the process design were not available and were excluded from this report. According to the information that we received from Altex, the CBTL process in this study has several main operational sections, including feedstock drying and size reduction, pyrolysis and steam cracking, fractionation and quenching, oligomerization, and fuel fractionation (Figure 2). First, the biomass and coal feedstocks are dried and ground into small particles to ensure rapid reaction in the pyrolysis reactor. Then the feedstocks are thermally decomposed in the pyrolysis and steam cracking section. The produced raw olefins are sent to the fractionation and quenching section. After that, the raw-olefin oil from the steam cracker is fractionated into olefins and other components. Olefins are fed to the oligomerization reactor. Finally, the mixture of products is fractionated into final products of jet fuel and diesel. In this study, owing to data limitations, we consider the CBTL process as an aggregated black box (a system process). Table 4 lists the aggregated material and energy flow data for this conversion process under the scenarios of Char-LF and Char-CHP (as shown in Figure 1). We assumed that densified biomass would consume the same amount of energy as non-densified biomass, although their moisture contents are

different. The CBTL process has a very high char yield: 0.33 ton char/ton feedstock is equivalent to 9.23 MMBtu/ton feedstock. As compared to the yields for jet fuel and diesel (3.61 and 2.20 MMBtu/ton feedstock, respectively), the char accounts for 61% of total energy outputs. Therefore, the utilization of char (namely, disposal to landfill and combustion for energy recovery) is an important issue in this CBTL process.

Under the scenario of Char-LF, external electricity and NG demands for the process are 105,160 and 147,829 Btu/MMBtu fuel outputs (the sum of diesel and jet), respectively, since no energy is recovered. Assuming that the landfill is close to the refinery (5.0 miles away), we took into account additional energy and emissions associated with char transportation to the landfill by heavy heavy-duty trucks (Argonne National Laboratory 2015). Char contains a large amount of C. With 15 wt% of biomass share in the total feedstock, the C content of char is 28 kg C/MMBtu of char, and 90% of this C is fossil C while the remaining 10% is biogenic C (Altex Technologies Corporation 2016). Under a carbon neutrality assumption, the 10% C in the char gets biogenic CO₂ credit, since this C is absorbed from the atmosphere via photosynthesis during biomass growth. When the char is buried in landfills, we assume that 80% (by mass) of the C in the char is stable and sequestered, and 20% is labile C and is converted to CO₂ over time (Han et al. 2013). These CO₂ emissions from 20% of the C in the char are taken into account as emissions. In this Char-LF scenario, char is considered as a waste rather than a coproduct displacing conventional products.

Under the Char-CHP scenario, we assumed that the CHP has 33% electricity efficiency and 64% heat recovery efficiency (the fraction of the useful heat recovered after electricity generation). The electricity and heat outputs from the CHP are 527,706 and 682,604 Btu/MMBtu fuel outputs, respectively. The generated electricity and heat first satisfy internal energy demands for the CBTL process; then excess electricity and heat are exported. The excess amounts of electricity and heat are 422,546 and 564,343 Btu/mmBtu available for export, respectively. This study assumes that all exported heat and electricity are used completely, displacing conventional heat (generated from a NG boiler with 80% efficiency) and electricity (U.S. average generation mix). While electricity can be transmitted easily, heat or steam must be consumed by nearby plants. Thus, this heat demand assumption could limit the potential location and size of plants or affect the WTWa results significantly when there is not enough heat demand.

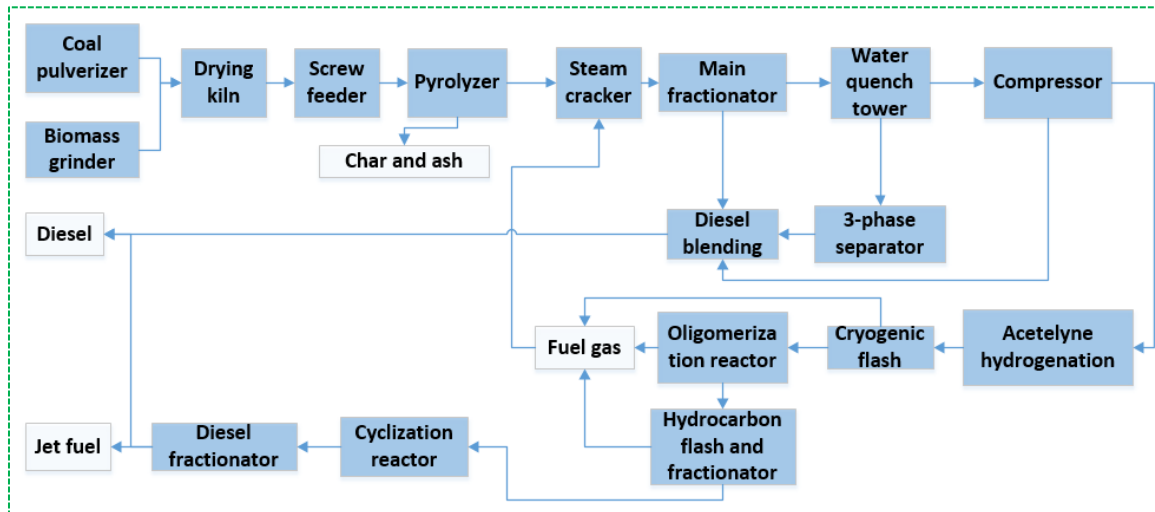


Figure 2. Process flow diagram for conversion of combined coal and biomass to liquid fuels (CBTL)

Table 4. Fuel yields and overall materials and energy inputs and outputs of the CBTL process^a

	Component	Char to Landfill	Char for CHP
Fuel yields	Jet fuel (MMBtu/ton feedstock)	3.61	3.61
	No. 2 diesel (MMBtu/ton feedstock)	2.20	2.20
Char yield	Char (ton/ton feedstock) ^b	0.33	0
Feedstocks:	Biomass (dry ton/MMBtu fuel)	0.0258	0.0258
	Lignite coal (dry ton/MMBtu fuel)	0.1463	0.1463
Energy use:	Electricity (Btu/MMBtu fuel)	105,160	0
	NG (Btu/MMBtu fuel)	147,829	0
Outputs	Jet fuel (MMBtu/MMBtu fuel)	0.622	0.622
	No. 2 diesel (MMBtu/MMBtu fuel)	0.378	0.378
	Char (ash free dry ton/MMBtu fuel)	0.057	0
	Exported electricity (Btu/MMBtu fuel)		422,546
	Exported heat (Btu/MMBtu fuel) ^c	0	564,343

^aValues are per MMBtu of combined jet and diesel fuels, which means that these inputs and outputs are already allocated on an energy basis.

^bLignite char (dry ash free) LHV is 33 MJ/kg with 86 wt% C content and biomass char (dry ash free) LHV is 23 MJ/kg with 79 wt% C content (Altex Technologies Corporation 2016) .

^c80% of NG boiler efficiency.

Owing to the large amount of coproduced electricity and heat, the WTWa results of the Char-CHP scenario depend highly on the coproduct handling method (Wang, Huo, and Arora 2011). The displacement and allocation methods are widely used to handle

coproducts in LCA. The displacement method (Char-CHP-Disp) allocates all energy and emission burdens to the main product, while the energy and emissions related to the displaced products are taken as credits. The energy allocation method (Char-CHP-EnAllo) allocates all energy and emission burdens among all products by their energy, mass, or market value shares. Note that while the Char-CHP scenarios coproduce heat and electricity, the char in the Char-LF scenario is not a coproduct but waste, whose energy and emissions burdens are allocated to jet fuel and diesel. For both scenarios, this study used an energy allocation between jet fuel and diesel. To handle heat and electricity in the Char-CHP scenario, this study examined two coproduct handling methods: Char-CHP-Disp and Char-CHP-EnAllo (Figure 1).

The emissions from char combustion in CHP are taken into account. The CHP emission factors of VOCs, CO, CH₄, and N₂O are 1.50, 12.4, 1.06, and 1.59 g/MMBtu of char burned, respectively, which are based on GREET 2015 (Argonne National Laboratory 2015). Fossil CO₂ emissions of the CHP process are calculated on the basis of C content in char, fossil C ratio, and C contents of VOCs, CO and CH₄. After counting C contents of VOCs, CO, and CH₄, the fossil CO₂ emission factor is 89,743 g/MMBtu char burned in the CHP process. Biogenic CO₂ emissions from the CHP process are treated as carbon-neutral. In this study, we also considered that the CHP process needs makeup and cooling water. However, since we did not have dedicated CHP process water consumption data, we assumed its water use is the same as for a coal-fired power plant (100.3 gal/MMBtu of electricity available at user sites) (Argonne National Laboratory 2015).

2.4 JET FUEL TRANSPORTATION AND DISTRIBUTION

Figure 3 shows jet fuel transportation and distribution assumptions used in this study (Argonne National Laboratory 2015). We assumed that jet fuel is produced domestically, so the share of ocean tank transportation is 0%. First, jet fuel is transported by barge (200 miles and 48.5% share), pipeline (100 miles and 46.4% share), and rail (490 miles and 5.1% share); then jet fuel is distributed from a bulk terminal to refueling stations by heavy heavy-duty trucks (30 miles and 100% share). The fuel types used for barge, pipeline, rail, and truck transportation are different, and include residual oil, electricity, and diesel (Figure 3). The direct and indirect (upstream) GHG emissions, energy consumption, and water use of jet fuel transportation and distribution are calculated using the default values from Argonne National Laboratory (2015).

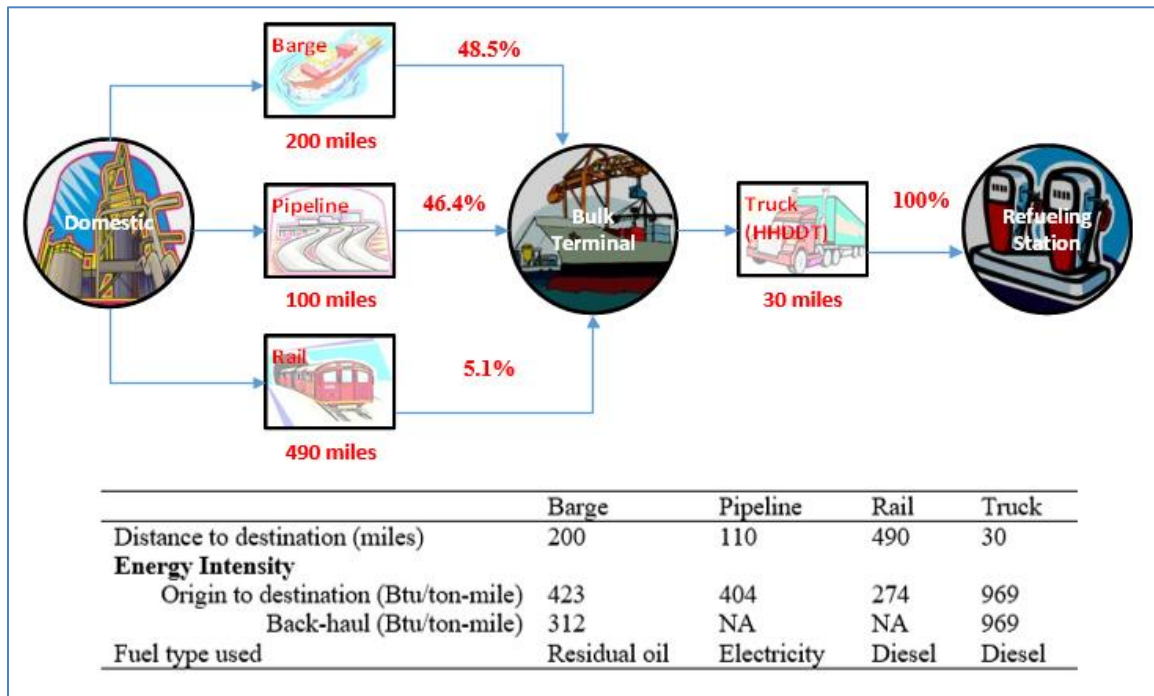


Figure 3. Jet fuel transportation and distribution assumptions used in this study

2.5 JET FUEL COMBUSTION IN AIRCRAFT

The aircraft selected for this study is the single-aisle passenger aircraft. Its emission factors for VOC, CO, CH₄, and N₂O are 1.29×10^{-2} , 9.14×10^{-2} , 1.06×10^{-4} , and 2.08×10^{-4} g/MJ of jet fuel, respectively, which are based on GREET 2015. Combustion fossil CO₂ emissions are calculated on the basis of jet fuel LHV (43.20 MJ/kg), total C ratio (86.2 wt%), fossil C ratio, and C contents of VOC, CO and CH₄. The fossil C ratio in jet fuel is dependent on the shares of biomass and coal in feedstocks. When biomass accounts for 15 wt% of feedstocks, the ratio of fossil C/total jet fuel C is 78 wt% (Altex Technologies Corporation 2016). After counting the C contents of VOCs, CO, and CH₄, the fossil CO₂ emission factor is 57 g/MJ jet fuel combusted in the single-aisle passenger aircraft. Biogenic CO₂ emissions from jet fuel combustion are carbon-neutral.

3. RESULTS AND DISCUSSION

3.1 FEEDSTOCK GHG EMISSIONS (FIELD TO REFINERY)

Figure 4 shows GHG emissions of bio-feedstocks (corn stover, switchgrass, and wheat straw) compared to lignite coal; these include emissions from farming and collection; field treatment, drying, handling and storage; biomass densification; and biomass transportation to the refinery gate. Bio-feedstocks have higher GHG emissions (76,664–142,075 gCO_{2e}/ton feedstock) than lignite coal (52,167 gCO_{2e}/ton feedstock). Supplemental fertilizer and chemical usage contributes 45–75% of the GHG emissions, followed by farming and collection (14–28%). Fertilizer production is very energy-intensive and generates high GHG emissions; in addition, a significant amount of N₂O emission (1.525%, Table 2) is generated once N fertilizer is applied to the soil (Argonne National Laboratory 2015). Among the bio-feedstocks examined, switchgrass produces the highest GHG emissions, owing mainly to its high N fertilizer demand and related N₂O emissions. In order to produce uniform and dense feedstocks, we assumed that biomass bales are further densified into pellets for the cases examined in this study. As shown in Table 3, compared to the bulk densities of biomass bales (137–169 kg/m³), the process of densification increased biomass bulk density by a factor of ~4. In addition, the process of densification decreased biomass moisture by 6%. For biomass bales, owing to their relatively low bulk density, the volume capacity (106 m³) of the truck is the limiting factor for biomass transportation. On the other hand, for biomass pellets, the weight capability (25 tons) of the truck is the limiting factor for biomass transportation. Compared to the transportation of biomass bales, owing to reduction of transportation energy consumption on a per-ton-of-dry-biomass-delivered basis, the transportation of biomass pellets could reduce GHG emissions by 5,267 gCO_{2e}/ton for corn stover and wheat straw and 2,842 gCO_{2e}/ton for switchgrass (Figure 4). The difference in reduction between switchgrass and the other two feedstocks (corn stover and wheat straw) is due to the difference in the biomass bulk densities of bales and pellets (bulk density ratio of pellets/bales: 641/169 = 3.8 for switchgrass, and 587/137 = 4.3 for corn stover and wheat straw). However, the emission burden of the densification process that results from electricity and NG demands is 20,090 gCO_{2e}/ton. From the viewpoint of overall GHG emissions (bales vs pellets: 95,025 vs 107,419 gCO_{2e}/ton for corn stover, 127,877 vs 142,075 gCO_{2e}/ton for switchgrass, and 76,664 vs 89,421 gCO_{2e}/ton for wheat straw), the densification process (bales to pellets) becomes unfavorable, with additional energy inputs (Figure 4). However, biomass densification results should be interpreted with caution, as the underlying densification energy (Altex Technologies Corporation 2016) is process-dependent and not fully optimized here. In addition, the energy requirement for biomass transportation is highly location-dependent. Altex proposed several potential sites: western North Dakota, southeast Texas, and eastern Montana (Table 5). Site-specific transportation information (such as distance and truck vs. rail) could be revisited as joint efforts by Altex and its partners continue. In addition, biomass densification could improve biomass logistics and release stringent constraints of collocation of coal and biomass resources, because biomass densification can reduce the cost of transportation and simplify storage and handling infrastructure.

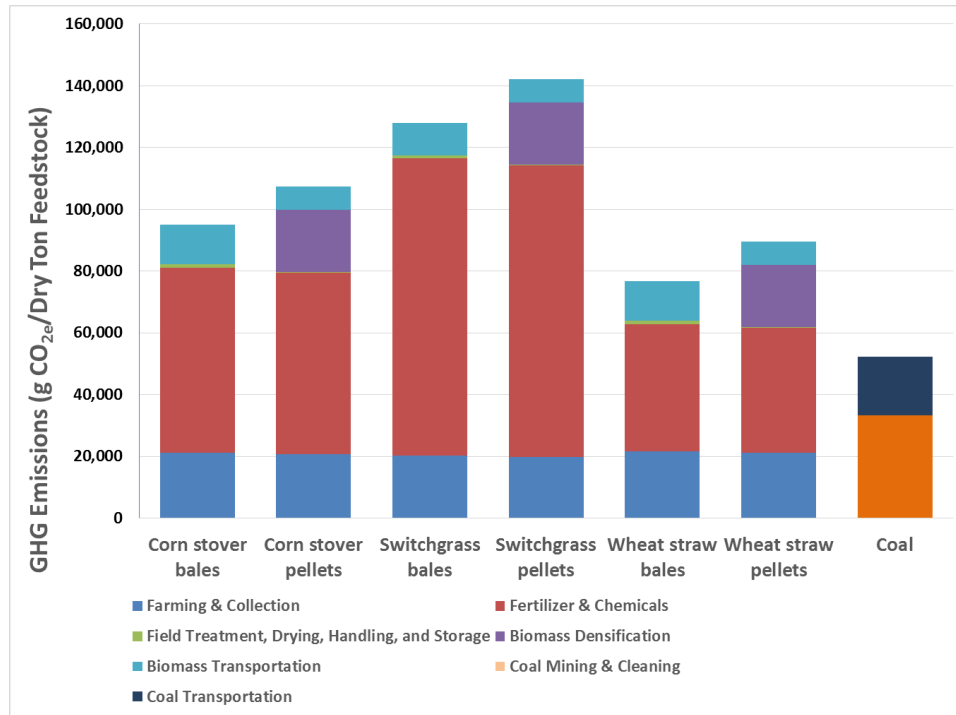


Figure 4. Greenhouse gas (GHG) emissions of feedstock process steps, compared to lignite coal, including farming and collection; field treatment, drying, handling, and storage; biomass densityfication; and biomass transportation to the refinery gate.

Table 5. Potential sites for the CBTL plant^a

Region	Feedstock type	Special characteristics
Western North Dakota	Lignite	Strong State support; biomass is plentiful.
Southeast Texas	Lignite	Forest residues and agriculture residues are plentiful.
Eastern Montana	Sub-bituminous	Huge reserves

^aSource: Altex Technologies Corporation (2016)

3.2 CARBON BALANCE AND WTWA GHG EMISSIONS FOR THE BASE CASE OF 85 WT% COAL AND 15 WT% BIOMASS

To simplify the presentation, the following discussion presents results for densified wheat straw only. Similar results for other feedstocks are included in Appendix Table A-1. The share of biomass in feedstocks is an important factor for life-cycle GHG emissions (Xie, Wang, and Han 2011). Altex assumed that 85% of mass was from coal, and 15% of mass was from wheat straw. As shown in Figure 5, through the CBTL process, 13.8% of C

is converted into jet fuel, 8.6% of C is converted into No 2 diesel, 30.6% of C is transformed into process CO₂ emissions that are captured by the CO₂ absorber with the efficiency of 95%, and the remaining C (47.0%) is left in the char. The carbon-to-fuel efficiency (including diesel) is 22.4%. Under the scenario of Char-LF, 20% of the C in the char (7.6 g fossil C/MJ and 0.8 g biogenic C/MJ) is emitted as CO₂, and 80% of the C in the char (30.3 g fossil C/MJ and 3.2 g biogenic C/MJ) is sequestered. The fossil labile C in the char (7.6 g C/MJ) is counted as GHG emissions, and the biogenic stable C in the char (3.2 g C/MJ) takes biogenic CO₂ credit. Thus, the net CO₂ emissions from char disposal are estimated at 15.9 g CO₂e/MJ (or 4.4 g C/MJ). Under the char-CHP scenario (Char-CHP-Disp or Char-CHP-EnAllo), both fossil C (37.9 g C/MJ fuel) and bio-C (4.0 g C/MJ fuel) are combusted. Bio-CO₂ is carbon neutral, and fossil-CO₂ is counted as GHG emissions. Under all scenarios, 95% of the CO₂ emissions from the CBTL process is captured and sequestered. The biogenic CO₂ in the captured CO₂ (1.36 g C/MJ fuel) is counted as carbon credits while 1.29 g C/MJ fuel is taken as GHG emissions. Thus, net GHG emissions from the process emissions after carbon capture is -0.07 g C/MJ. Bio-CO₂ from fuel combustion in aircraft (2.6 gC/MJ fuel) is carbon-neutral (Figure 5).

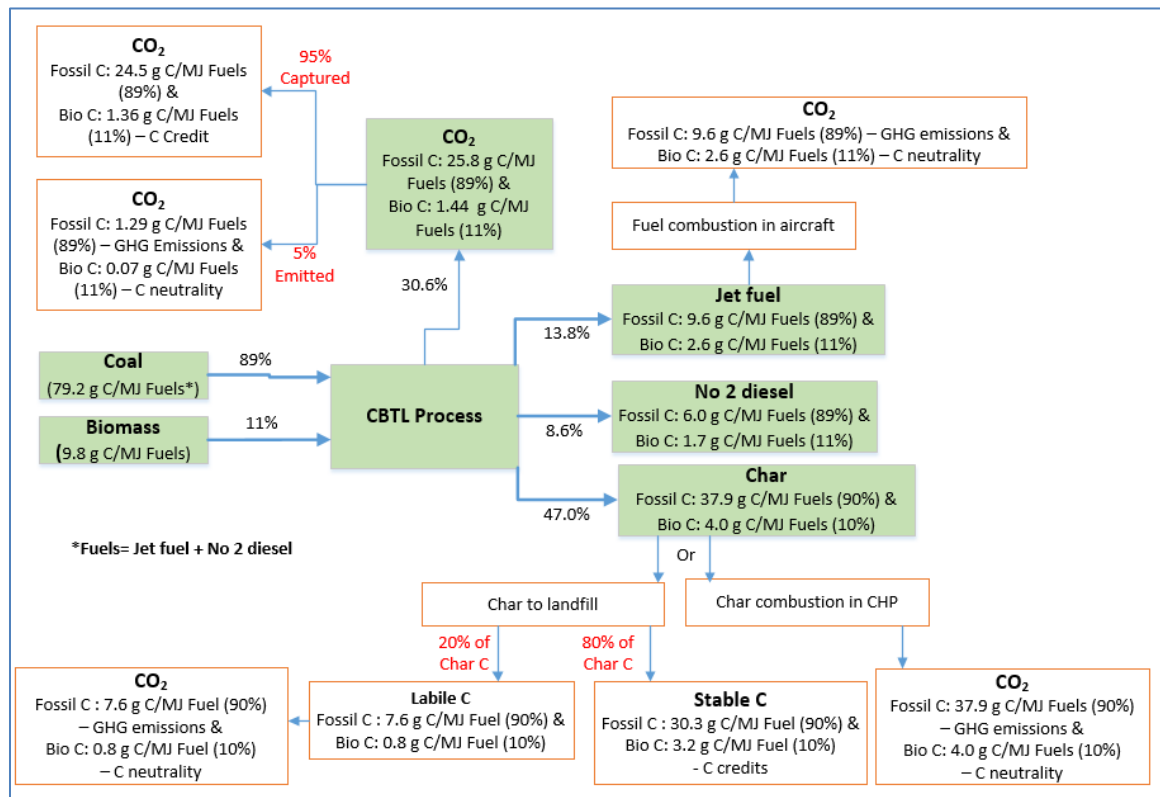


Figure 5. Carbon balance for the case of 85 wt% coal and 15 wt% biomass

The WTWa GHG emissions of jet fuel from the CBTL process, compared to conventional jet fuel, are shown in Figure 6. For conventional jet fuel, GREET evaluates GHG emissions from crude oil recovery and transportation, refining to jet fuel, jet fuel transportation and distribution, and end use (Argonne National Laboratory 2015). As shown in Figure 6, when biomass accounts for 15% of the total feedstock mass, the jet fuel from the CBTL process has higher WTWa GHG emissions than conventional jet fuel (84 g CO_{2e}/MJ). Of the three char application scenarios, Char-CHP-Disp has the lowest GHG emissions (97 g CO_{2e}/MJ), and followed by Char-LF. In the Char-CHP-Disp scenario, the combusted fossil C in the CHP contributes 136 CO_{2e}/MJ of GHG emissions, and the displacement credits from excess CHP electricity and heat are 112 gCO_{2e}/MJ. When char is sent to a landfill, the processes of char transportation, along with fossil CO₂ from labile carbon, contribute 28 CO_{2e}/MJ of GHG emissions. In the Char-CHP-EnAllo scenario, exported electricity and heat from CHP allocate 50% of the energy and emissions burdens from the processes of feedstocks, fuel process, and CHP. As shown in Figure 6, direct emission from char combustion in the CHP is the largest contributor in the Char-CHP scenario (Char-CHP-Disp or Char-CHP-EnAllo). The net jet fuel combustion (fossil CO_{2e}) contributes 55%, 65% and 46% of WTWa GHG emissions under the Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo scenarios, respectively. Biomass and coal feedstocks are not major contributors to WTWa GHG emissions, contributing 8.1%, 9.7% and 3.5% of WTWa GHG emissions under the Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo scenarios, respectively.

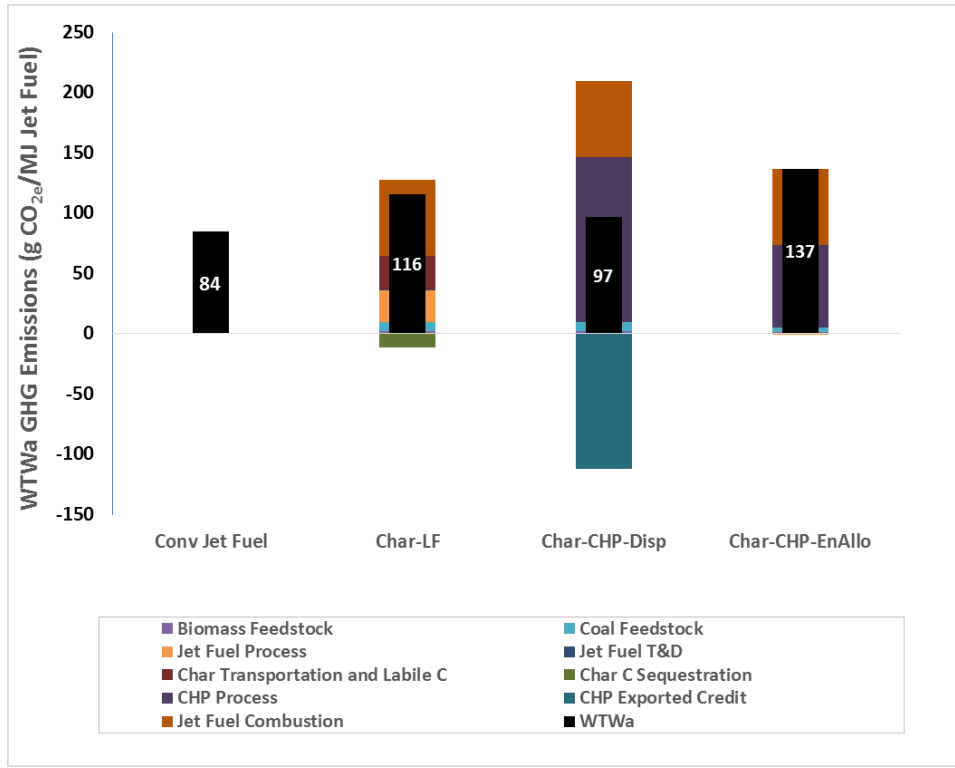


Figure 6. WTWa GHG emissions from 15% wheat straw biomass and 85% lignite coal under three scenarios: char to landfill (Char-LF), char for CHP-displacement (Char-CHP-Disp), and char for CHP-energy allocation (Char-CHP-EnAllo).

3.3 WTTWA WATER USE FOR THE BASE CASE OF 85 WT% COAL AND 15 WT% BIOMASS

As shown in Figure 7, besides impacting GHG emissions, char handling methods also have significant impact on WTTWA water use. When char is used for CHP, the CBTL process energy demand is satisfied internally. The net water uses for the CBTL process, which are direct process water demand, are 0.0271 and 0.0137 gal/MJ fuels under the Char-CHP-Disp and Char-CHP-EnAllo scenarios, respectively. On the other hand, under the Char-LF scenario, the net water use for the CBTL process is 0.0623 gal/MJ fuel, which includes both direct process and indirect upstream water demands. Direct water uses in the CHP processes (0.0502 gal/MJ for Char-CHP-Disp and 0.0252 gal/MJ for Char-CHP-EnAllo) are the largest contributors. The water usage of biomass is 0.0020, 0.0020, and 0.0010 gal/MJ under the Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo scenarios, respectively. The water usage of coal is 0.0074, 0.0074, and 0.0037 gal/MJ under the Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo scenarios, respectively. The water use credit

is -0.133 gal/MJ under the Char-CHP-Disp scenario. Overall, the WTWa water usages are 0.072, -0.046 (water saving), and 0.044 gal/MJ under the Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo scenarios, respectively. The Char-CHP-Disp and Char-CHP-EnAllo scenarios could achieve 266% and 59% water use reduction compared to conventional jet fuel. The Char-LF scenario increases water use by 161% compared to conventional jet fuel. As shown in Figure 7, under the Char-LF scenario, the fuel process is the major contributor to water use. One good option to minimize freshwater use is to recycle process water.

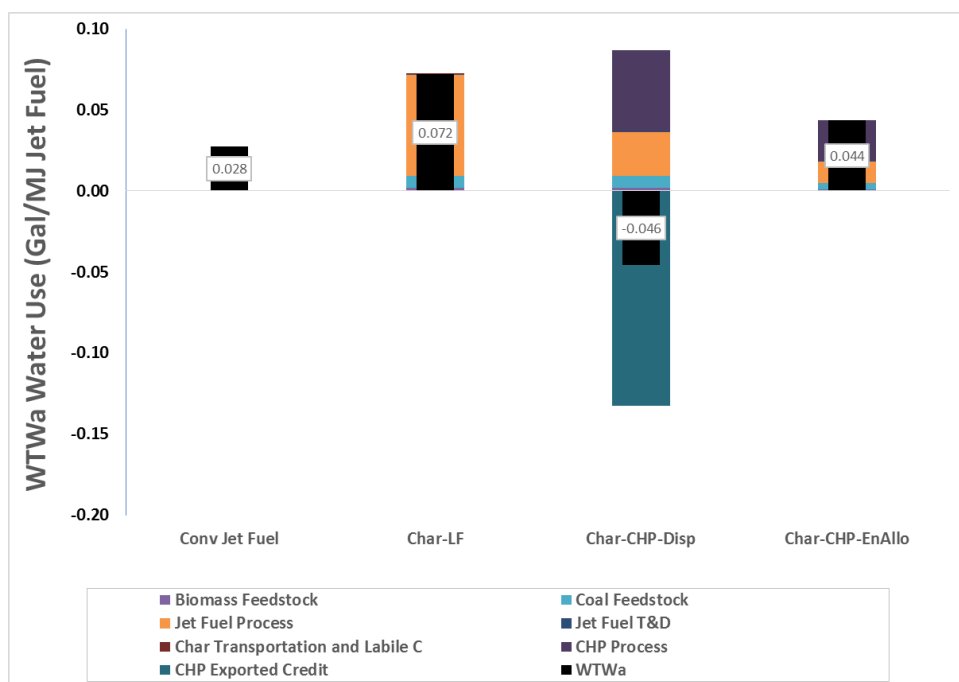


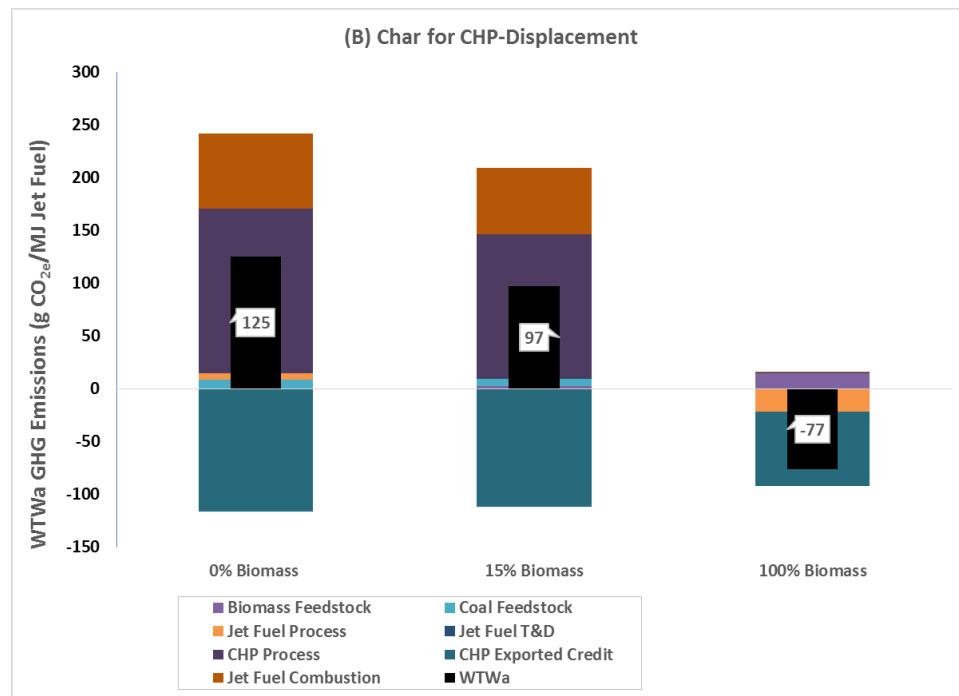
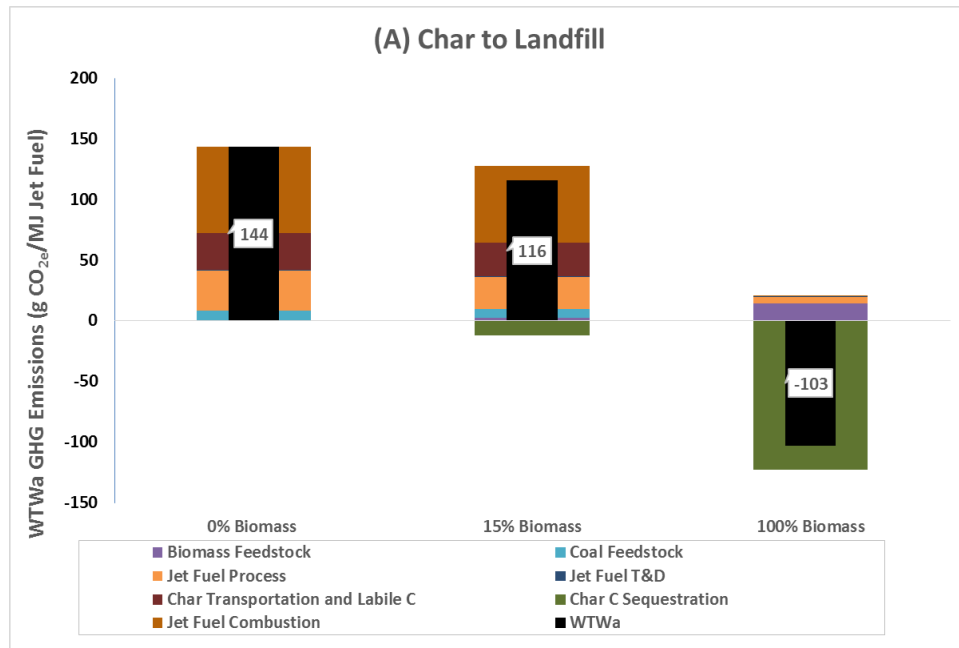
Figure 7. WTWa water use from 15% wheat straw biomass and 85% lignite coal under three scenarios: char to landfill (Char-LF), char for CHP-displacement (Char-CHP-Disp), and char for CHP-energy allocation (Char-CHP-EnAllo).

3.4 PATHS FORWARD TO 84 gCO_{2e}/MJ

According to the Energy Independence and Security Act (EISA) of 2007, U.S. Federal agencies cannot enter into contracts for procurement of an alternative fuel that has higher life-cycle GHG emissions than the equivalent conventional fuel (Public Law 110-140 2007). In this study, we did not receive data from Altex related to product yields and optimal process conditions with different biomass feedstock shares. To study biomass share sensitivity and estimate proximate break-even points, we assumed that the yields of jet fuel, diesel and char are 3.61 MMBtu/ton feedstock, 2.20 MMBtu/ton feedstock, and 0.33 ton/ton feedstock, respectively (Table 4). Also, we assumed that the energy demands for

electricity and NG are 105,160 and 147,829 Btu/MMBtu fuels, respectively (Table 4). However, these assumptions are not faultless, and Altex is advised to revisit and evaluate these assumptions in the future when new experimental data are available. Han et al. (2013) showed that the product yields (oil, gas, char and water) vary with biomass feedstocks (woody vs. herbaceous), and different feedstocks have different optimal temperatures and pressures for pyrolysis to maximize product yields. Under the assumptions of constant energy demands and fuel yields regardless of the share of biomass and coal feedstocks, the analysis presented below demonstrates a strategy for reducing WTWa GHG emission to 84 gCO_{2e}/MJ (equivalent to conventional jet fuel) by changing biomass shares (from 0 to 100%) in the feedstock. Figure 8 shows WTWa GHG emissions of 0%, 15%, and 100% biomass under the three scenarios of Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo. Compared to conventional jet fuel (84 gCO_{2e}/MJ), jet fuel from coal alone (0% biomass) increases life-cycle GHG emissions by 70%, 48%, and 84% under the Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo scenarios, respectively (Figure 8 A-C). Xie, Wang, and Han (2011) reported similar results, namely, that FT diesel from coal increases life-cycle GHG emissions by more than 200% without CCS and 5–29% with CCS, relative to petroleum diesel. When biomass is used as the sole feedstock (100% biomass), jet fuel from the CBTL process decreases life-cycle GHG emissions by 222%, 191%, and 105% under the Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo scenarios, respectively. In the Char-LF scenario, the process with 100% biomass results in 103 g CO_{2e}/MJ carbon sequestration (negative WTWa emissions). In the Char-CHP-Disp scenario, excess electricity and heat are exported to displace conventional products (U.S. average generation mix and NG), and the displacement credits are over 70 g CO_{2e}/MJ.

Figure 9 shows the break-even point of 84 gCO_{2e}/MJ for the CBTL process under three scenarios. The Char-CHP-Disp scenario needs the lowest biomass supplementation (23%) to achieve WTWa GHG emissions of 84 gCO_{2e}/MJ, and followed by the Char-LF scenario (31%) and the Char-CHP-EnAllo (53%). In the Char-LF scenario, GHG emissions from jet fuel combustion, char transportation-labile C emissions, and fuel processes are 54, 23, and 26 gCO_{2e}/MJ, respectively (Figure 9). In this case, optimizing the fuel process could be a good option to further reduce GHG emissions. In the Char-CHP-Disp scenario, GHG emissions from the CHP process, jet fuel combustion, and CHP exported credits are 122, 59, and -108 gCO_{2e}/MJ, respectively (Figure 9). In the Char-CHP-EnAllo scenario, GHG emissions from CHP process and jet fuel combustion are 41 and 40 gCO_{2e}/MJ, respectively (Figure 9). In both Char-CHP scenarios, a CHP with an integrated CCS could be a good option to further reduce GHG emissions. A caveat is that the displacement approach might be problematic for this study. The large credits and net negative GHG emissions obtained with the displacement method indicate the likelihood of distorted results (Wang, Huo, and Arora 2011).



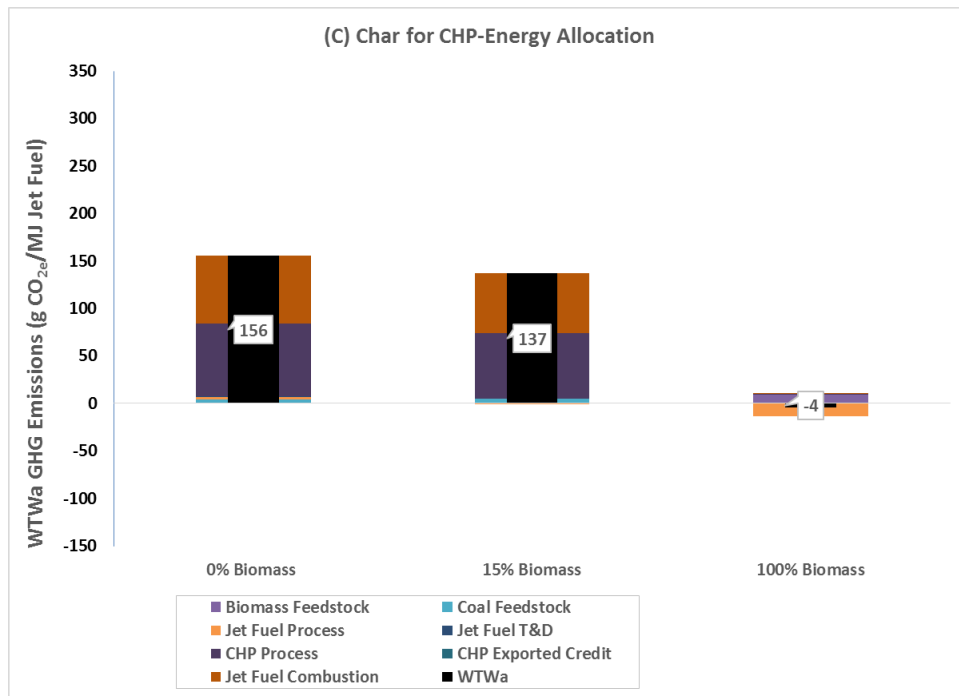


Figure 8. Impact of biomass shares (0%, 15%, and 100%) and char handling on WTWa GHG emissions of jet fuel. (A) char to landfill (Char-LF), (B) char for CHP-displacement (Char-CHP-Disp), and (C) char for CHP-energy allocation (Char-CHP-EnAllo)

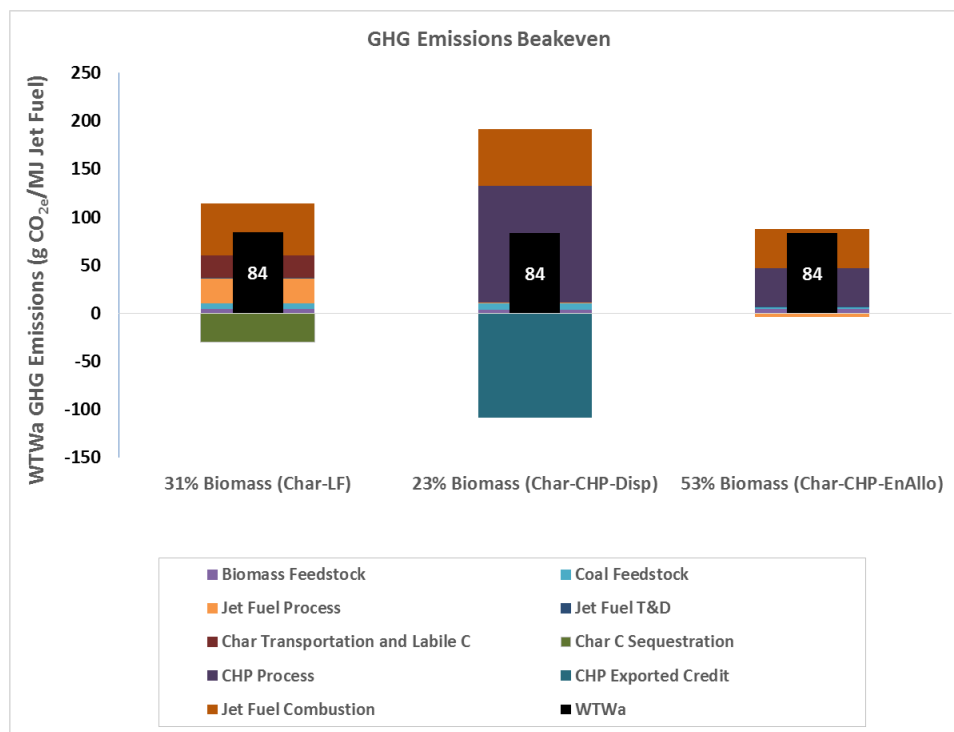


Figure 9. Paths forward to 84 g CO_{2e}/MJ for the combined coal and biomass to liquid fuels (CBTL) pathway under three scenarios: char to landfill (Char-LF), char for CHP-displacement (Char-CHP-Disp), and char for CHP-energy allocation (Char-CHP-EnAllo).

4. CONCLUSIONS

The present report evaluates life-cycle GHG emissions and water usage of combined coal and biomass conversion to liquid fuels. Among corn stover, switchgrass and wheat straw, switchgrass has the greatest GHG emissions (per dry ton feedstock), which are mainly due to its high N fertilizer demand and related N₂O emissions. From the viewpoint of overall GHG emissions (per dry ton feedstock), the densification process (bales to pellets) becomes unfavorable, with additional biomass process energy demand. When the feedstock contains 15 wt% densified wheat straw and 85 wt% lignite coal, compared to conventional jet fuel at 84 gCO_{2e}/MJ, WTWa GHG emissions are 116, 97, and 137 gCO_{2e}/MJ under the Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo scenarios, respectively. WTWa water consumption is 0.072, -0.046, and 0.044 gal/MJ for Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo, respectively (compared to conventional jet fuel at 0.028 gal/MJ). The fuel process is the major contributor to the water usage, so to reduce WTWa water usage, one good option is to recycle the fuel process water and minimize

freshwater use. To reach the break-even point of 84 gCO_{2e}/MJ (emissions for petroleum fuels) and comply with the 2007 EISA, Section 526, “*Procurement and Acquisition of Alternative Fuels*,” under the assumptions of constant product yields and energy demands regardless of the share of biomass and coal feedstocks, 31 wt%, 23 wt%, and 53 wt% of the feedstock blend needs to be biomass under the Char-LF, Char-CHP-Disp, and Char-CHP-EnAllo scenarios, respectively. A caveat is that, owing to data source limitations, the assumptions of energy usage and product yields for different shares did not represent real conditions, and future improvement to reduce uncertainties is needed. Another issue is that the displacement approach might be problematic for this study. The large credits obtained with the displacement method indicate the likelihood of distorted results. Moving forward, development efforts to further reduce GHG emissions should focus on CCS integration, effective coproduct utilization, fuel process energy reduction and yield improvement, and feedstock production and logistics optimization.

5. BIBLIOGRAPHY

- Altex Technologies Corporation. 2016. "Combined coal and biomass to liquid fuels (CBTL) process." Email communication, 2016.
- Argonne National Laboratory. 2015. "The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model." <http://greet.es.anl.gov>.
- Argonne National Laboratory. 2016. Summary of Expansions, Updates, and Results in GREET 2016 Suite of Models. <http://greet.es.anl.gov>.
- Burnham, Andrew, Jeongwoo Han, Corrie E. Clark, Michael Wang, Jennifer B. Dunn, and Ignasi Palou-Rivera. 2012. "Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum." *Environmental Science & Technology* 46 (2):619-627. doi: 10.1021/es201942m.
- Canter, C. E., J. B. Dunn, J. Han, Z. C. Wang, and M. Wang. 2016. "Policy Implications of Allocation Methods in the Life Cycle Analysis of Integrated Corn and Corn Stover Ethanol Production." *Bioenergy Research* 9 (1):77-87. doi: 10.1007/s12155-015-9664-4.
- Canter, C. E., Z. C. Qin, J. B. Dunn, and M. M. Wander. 2016. Update to Herbaceous and Short Rotation Woody Crops in GREET® Based on the 2016 Billion Ton Study. Argonne, IL: Argonne National Laboratory.
- Department of Defence. 2014. Feasibility of Technologies to Produce Coal-Based Fuels with Equal or Lower Greenhouse Gas Emissions than Petroleum Fuels.
- Han, J., A. Elgowainy, H. Cai, and M. Q. Wang. 2013. "Life-cycle analysis of bio-based aviation fuels." *Bioresour Technol* 150:447-56. doi: 10.1016/j.biortech.2013.07.153.
- Han, J., L. Tao, and M. Wang. 2017. "Well-to-wake analysis of ethanol-to-jet and sugar-to-jet pathways." *Biotechnol Biofuels* 10:21. doi: 10.1186/s13068-017-0698-z.
- Intergovernmental Panel on Climate Change. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4 Agriculture, Forestry and Other Land Use. .
- Lampert, D. , H. Cai, Z. C. Wang, J. Keisman, M. Wu, J. Han, J. B. Dunn, J. Sullivan, A. Elgowainy, M. Wang, and J. Keisman. 2015. Development of a Life Cycle Inventory of Water Consumption Associated with the Production of Transportation Fuels. Argonne National Laboratory.
- Lampert, D. J., H. Cai, and A. Elgowainy. 2016. "Wells to wheels: water consumption for transportation fuels in the United States." *Energy & Environmental Science* 9 (3):787-802. doi: 10.1039/c5ee03254g.
- National Academy of Sciences. 2009. *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts*: The National Academies Press.
- Public Law 110-140. 2007. Energy Independence and Security Act of 2007 U.S. Government Information.

- U.S. Department of Energy. 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. edited by M. H. Langholtz, B. J. Stokes and L. M. Eaton. Oak Ridge National Laboratory, Oak Ridge, TN.
- US EIA. 2016. Annual energy outlook 2016. Washington, DC: US Energy Information Administration.
- US EIA. 2017. "U.S. Energy Information Administration: Today in Energy." accessed March 25, 2017.
<https://www.eia.gov/todayinenergy/detail.php?id=30432>.
- Wang, M. Q., J. Han, Z. Haq, W. E. Tyner, M. Wu, and A. Elgowainy. 2011. "Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes." *Biomass & Bioenergy* 35 (5):1885-1896. doi: 10.1016/j.biombioe.2011.01.028.
- Wang, Michael, Hong Huo, and Salil Arora. 2011. "Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the U.S. context." *Energy Policy* 39 (10):5726-5736. doi: 10.1016/j.enpol.2010.03.052.
- Xie, X., M. Wang, and J. Han. 2011. "Assessment of fuel-cycle energy use and greenhouse gas emissions for Fischer-Tropsch diesel from coal and cellulosic biomass." *Environ Sci Technol* 45 (7):3047-53. doi: 10.1021/es1017703.

APPENDIX

Table A-1: WTWa GHG emissions and water use of different biomass feedstocks

Biomass component*	Char-LF		Char-CHP-Disp		Char-CHP-EnAllo	
	WTWa GHG emissions (g CO _{2e} /MJ jet fuel)	WTWa water use (gal/MJ jet fuel)	WTWa GHG emissions (g CO _{2e} /MJ jet fuel)	WTWa water use (gal/MJ jet fuel)	WTWa GHG emissions (g CO _{2e} /MJ jet fuel)	WTWa water use (gal/MJ jet fuel)
Corn Stover (Bales)	113.03	0.072	94.38	-0.046	135.07	0.044
Corn Stover (Pellets)	113.34	0.073	94.68	-0.045	135.22	0.044
Switchgrass (Bales)	113.94	0.071	95.29	-0.047	135.54	0.044
Switchgrass (Pellets)	114.29	0.072	95.63	-0.046	135.71	0.044
Wheat Straw (Bales)	115.45	0.071	96.81	-0.046	136.68	0.044
Wheat Straw (Pellets)	115.77	0.072	97.12	-0.046	136.84	0.044

*Biomass (15 wt%):Coal (85 wt%)

ACRONYMS AND ABBREVIATIONS

Altex	Altex Technologies Corporation
CBTL	Coal and biomass (conversion) to liquid fuels
CCS	Carbon capture and storage
CH ₄	Methane
Char-CHP	Char for CHP
Char-CHP-Disp	Char for CHP displacement
Char-CHP-EnAllo	Char for CHP energy allocation
Char-LF	Char for landfill disposal
CHP	Combustion for combined heat and power
CTL	Coal (conversion) to liquid fuels
EISA	Energy Independence and Security Act
FT	Fischer-Tropsch
GHG	Greenhouse gas
REET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
HRJ	Hydroprocessed renewable jet
LCA	Life cycle analysis
LHV	Lower heating value
MJ	Megajoule
MPDGE	Miles per diesel gallon equivalent
NG	Natural gas
PTWa	Pump-to-Wake
VOC	Volatile organic compound
WTP	Well-to-Pump
WTWa	Well-to-Wake



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